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ROSSI X-RAY TIMING EXPLORER OBSERVATION OF PSR B0656+14

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ABSTRACT

PSR B0656+14 was observed by the *Rossi X-Ray Timing Explorer* (*RXTE*) with the proportional counter array (PCA) and the high-energy X-ray timing experiment (HEXTE) for 160 ks during 1997 August 22–September 3. No pulsation was firmly found in the timing analysis, during which the contemporaneous radio ephemeris and various statistical tests were applied in searching for evidence of pulsation. A marginal detection of pulsation at a confidence level of 95.5% based on the *H* test was found with data in the whole HEXTE energy band. In the energy band of 2–10 keV the *RXTE* PCA upper limits are about 1 order of magnitude lower than that from *ASCA* GIS data. If the *Compton Gamma Ray Observatory* EGRET detection of this pulsar is real, considering the common trait that most EGRET-detected pulsars have a cooling spectrum in hard X-ray and gamma-ray energy bands, the estimated *RXTE* upper limits indicate a deviation (low-energy turnover) from a cooling spectrum starting from 20 keV or higher. This in turn suggests an outer magnetospheric synchrotron radiation origin for high-energy emissions from PSR B0656+14. The *RXTE* PCA upper limits also suggest that a reported power-law component based on *ASCA* SIS data in 1–10 keV fitted jointly with *ROSAT* data, if real, should be mainly unpulsed.

Subject headings: pulsars: individual (PSR B0656+14) — X-rays: stars

1. INTRODUCTION

The pulsar PSR B0656+14 was discovered by Manchester et al. (1978) with a period of 384.9 ms, a characteristic age of 1.1×10^5 yr, and an inferred surface dipole magnetic field of 4.7×10^{11} G. After the report of its possible optical counterpart (Caraveo, Bignami, & Mereghetti 1994), its optical emission was recently observed to be pulsed at the radio period and shows a nonthermal origin (Shearer et al. 1997; Pavlov, Welty, & Córdova 1997; Kurt et al. 1998). X-ray pulsation at the period of PSR B0656+14 from the *Einstein* X-ray source E0656+14 was found by Córdova et al. (1989). Subsequent observations with *ROSAT* showed thermal characteristics with a hard tail in its spectrum in 0.1–2.4 keV, which can be fitted well by a helium-atmosphere blackbody model (Finley, Ögelman, & Kiziloğlu 1992) or a two-component model comprising either two blackbodies or a blackbody plus a power law (Possenti, Mereghetti, & Colpi 1996). Using *ACSA* data jointly with *ROSAT* data, Greiveldinger et al. (1996) found that a two-component model cannot fit the spectrum well, and a three-component model (two blackbodies plus a power law) gives an acceptable fit. However, a recent study (Wang et al. 1998) did not confirm the necessity of invoking the third (power law) component. At the high-energy end, PSR B0656+14 joined the EGRET-pulsar family with a relatively weak evidence of pulsation (Ramanamurthy et al. 1996). Like other EGRET pulsars, it shows a power-law spectrum in the EGRET energy band.

With the proposed power-law component from fitting *ROSAT* with *ASCA* data and that from the EGRET observation, it is apparent that the spectrum will bend, either gradually or more abruptly, between 10 keV and 100 MeV. Such a spectral bending can be used to constrain possible emission sites and mechanisms for these X-rays and gamma rays (Chang & Ho 1997). On the other hand, observations around 10 keV will help clarify the existence of the power-law component in the *ROSAT*/*ASCA* study. Here we report the results of a 160 ks *RXTE* Cycle 2 observation of PSR B0656+14 in the energy range of 2–250 keV. Although no pulsation was detected, our estimated upper limits for the pulsed flux are low enough to be used to support an outer magnetospheric synchrotron radiation origin for high-energy emissions from PSR B0656+14. They also suggest that the reported power-law component based on *ASCA* SIS data in 1–10 keV fitted jointly with *ROSAT* data, if real, should be mainly unpulsed.

2. OBSERVATION

The proportional counter array (PCA) and high-energy X-ray timing experiment (HEXTE) on board *RXTE* were pointed at PSR B0656+14 during 1997 August 22–September 3 (MJD 50,682–50,694) for about 160 ks. The *RXTE* mission, spacecraft, and instrument capabilities are described in Swank et al. (1995), Giles et al. (1995), and Zhang et al. (1993). The PCA consists of five essentially identical proportional counter units (PCUs) with a total effective area of 6729 cm^2. The HEXTE comprises two clusters of four scintillation counters. The net open area of the eight detectors is 1600 cm^2 (Rothschild et al. 1998). PCA and HEXTE have no imaging capability. Their field of view is 1°.

Data were first screened according to the following two criteria: (1) the offset, that is, the difference between the source position and the pointing of the satellite, is less than $0.^\circ02$; and (2) the elevation angle, that is, the angle between the Earth's limb and the target viewed from the satellite, is larger than 10°. During the whole observation, the five PCUs of the PCA were all on. The total exposure for the

TABLE 1

RADIO EPHEMERIS OF PSR B0656+14[a]

Measurement	Results
Validity interval (MJD)......	50,606–50,797
Epoch, t_0 (MJD)	50,701.000002341
α_{2000}	$6^h59^m48^s.126$
δ_{2000}	$14°14'21''.15$
ν (Hz)	2.5981054226747
$\dot{\nu}$ (Hz s^{-1})	-3.71150×10^{-13}
$\ddot{\nu}$ (Hz s^{-2})	8.33×10^{-25}

[a] Provided by Andrew Lyne (1998, private communication).

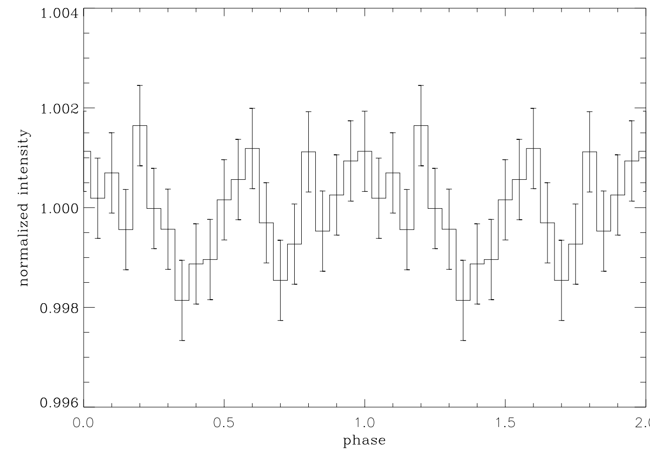

FIG. 1.—Folded light curve of PSR B0656+14 from *RXTE* HEXTE data, channels 14–234, 15–250 keV.

PCA is 152.4 ks $\times$ 6729 cm^2, which is equal to 1.026×10^9 s cm^2. One detector in cluster B of the HEXTE has lost its spectral capability, and we excluded all the photons detected by that detector in our analysis. The total exposure for the HEXTE is then 153.9 ks $\times$ 1600 $cm^2 \times \frac{7}{8}$, which is 2.155×10^8 s cm^2.

Around the same epoch of the *RXTE* observation, PSR B0656+14 was also monitored at Jodrell Bank Radio Observatory. The radio ephemeris is summarized in Table 1 and used as the input for pulsation search.

3. ANALYSIS AND RESULTS

The data were reduced to the solar system barycenter and analyzed using the JPL DE200 ephemeris, the pulsar position listed in Table 1, and the *RXTE*-related tasks in the software package FTOOLS v.4.0.

In the timing analysis, PCA data were divided into five energy bands, covering PCA channels 6–16 (2.1–6.1 keV), 17–26 (6.1–9.8 keV), 27–55 (9.8–20.5 keV), 56–107 (20.5–40.4 keV), and 108–249 (40.4–98.5 keV), respectively. The HEXTE data were also divided into three bands, HEXTE channels 14–60 (15–60 keV), 61–121 (60–125 keV), and 122–234 (125–250 keV). To search for pulsation, each detected photon was assigned an arrival phase ϕ based on the ephemeris in Table 1; ϕ = a fractional part of $[\nu(t - t_0) + \dot{\nu}(t - t_0)^2/2 + \ddot{\nu}(t - t_0)^3/6]$, where ν is the pulsar frequency, t the barycentric corrected arrival time of the photon, and t_0 the radio epoch. We then binned the photons in each energy band and various combinations of energy bands according to their arrival phases in order to form light curves with 20 and 40 bins in one period. The result was that none of the light curves shows significant deviation from a model steady distribution under the Pearson's χ^2 test (Leahy et al. 1983a; Leahy, Elsner, & Weisskopf 1983b).

We also applied the bin-independent parameter-free H test (De Jager, Swanepoel, & Raubenheimer 1989) to search for signature of pulsation. The H test was applied to the data in different energy bands and various combinations. The results of the H test all show a high probability of the data being consistent with a steady source. Only a very marginal detection of pulsation was found in the whole HEXTE energy band (channels 14–234, 15–250 keV), with a 95.5% probability of being inconsistent with a steady source based on the H test. The folded light curve in this energy band is shown in Figure 1. Applying the straight Z_1^2 test (the Rayleigh test, which is more appropriate if the underlying pulse profile is sinusoidal), the probability is 90.6%, while the Z_3^2 test gives a probability of 98.4%.

In our analysis, the χ^2 test and the H test were repeated in an interval of pulsation frequencies near the radio frequency. Unlike the spiky dependence of the χ^2 value on frequencies, the H test gives a smooth variation in the corresponding probability for different frequencies. None of these trials gives significant evidence of pulsation. A higher probability was found at a frequency lower than the radio frequency by 9×10^{-8} Hz. At this frequency, the H test gives a 98.2% probability of pulsation detection in the HEXTE data covering channels 14–234.

Based on these analyses, we do not consider the current observation to provide evidence of pulsation from PSR B0656+14 in the *RXTE* energy band.

The upper limit of pulsed flux is estimated following the prescription given by Ulmer et al. (1991). Assuming a duty cycle of 0.5, we obtain the following 3 σ upper limits, which are also shown in Figure 2: for PCA, 1.3×10^{-6} cm^{-2} s^{-1} keV^{-1} in 2.1–6.1 keV, 1.1×10^{-6} cm^{-2} s^{-1} keV^{-1} in 6.1–9.8 keV, 5.6×10^{-7} cm^{-2} s^{-1} keV^{-1} in 9.8–20.5 keV,

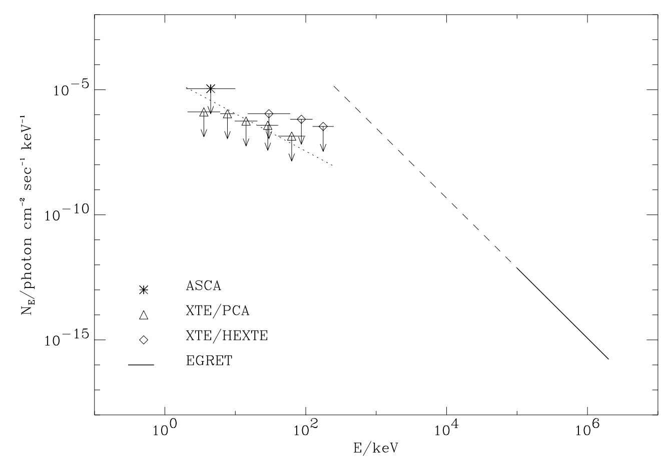

FIG. 2.—Spectrum of PSR B0656+14 from 2 keV up to 2 GeV. Upper limits are all for pulsed flux and at a 3 σ level. The *ASCA* upper limit in 2–10 keV is based on the *ASCA* GIS data (Greiveldinger et al. 1996). The dotted line is the power-law component with a photon spectral index of −1.5 proposed by Greiveldinger et al. (1996) from fitting *ASCA* SIS data in 1–10 keV together with *ROSAT* PSPC data, which includes both pulsed and unpulsed components. It was not confirmed by a later analysis (Wang et al. 1998). This power law is plotted in this figure with an extension to a higher energy. It intersects with the EGRET spectrum at about 100 MeV.

3.8×10^{-7} $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ in 20.5–40.4 keV, and 1.4×10^{-7} $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ in 40.4–98.5 keV; for HEXTE, 1.1×10^{-6} $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ in 15–60 keV, 6.6×10^{-7} $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ in 60–125 keV, and 3.4×10^{-7} $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$ in 125–250 keV.

4. DISCUSSION

In the study with *ROSAT* PSPC and *ASCA* SIS data, Greiveldinger et al. (1996) reported a three-component spectral model, which consists of two blackbodies with temperatures at 7.8×10^5 and 1.5×10^6 K and a power law with a photon spectral index of -1.5. Based on the *ASCA* GIS data, the pulsed fraction was estimated to be 71% as a 3 σ upper limit in 0.5–10 keV or 31% $\pm$ 10% at a 2 σ level of detection in 0.5–2 keV and 100% as a 3 σ upper limit in 2–10 keV. For comparison, the proposed power-law component, which includes both pulsed and unpulsed fluxes, and the 3 σ upper limit in 2–10 keV from *ASCA* GIS data for the pulsed flux are plotted in Figure 2. Our estimated 3 σ upper limits from *RXTE* PCA data in 2–10 keV are about 1 order of magnitude lower than that from *ASCA* GIS data. These new upper limits make it plausible that the spectrum of the pulsed flux below 20 keV, if detected, should have a photon spectral index larger than -1.5, assuming that the index increases from -2.8 above 100 MeV monotonically toward the lower energy end.

EGRET pulsars all have power-law spectra typically covering 2 orders of magnitude in the EGRET band with best-fit photon spectral indices in the range of -1.4 to -1.8, except for the Crab and PSR B0656+14 (Fierro 1995; Nolan et al. 1996; Merck et al. 1996). Their spectra all turn flatter at lower energies. For example, PSR B1951+32, although with a steeper spectrum in the EGRET band, has a spectrum with a photon spectral index of -1.5 around 1–10 MeV. This spectral behavior has been discussed and used to form an argument that provides a useful diagnostic to constrain possible emission locations and mechanisms for these high-energy emissions (Chang & Ho 1997). The key issue in that argument is a "bending energy" below which the spectrum starts deviating from a cooling one. A cooling spectrum is due to a cooling model of a steady-state electron/positron distribution and has a photon spectral index of $-3/2$ for the dominant cooling mechanism being synchrotron radiation and $-5/3$ for curvature radiation. In the parameter space of the electron/positron energy and the distance from the stellar center, which characterizes the strength of magnetic fields and the curvature radius of field lines, one can find a line along which the radiative cooling timescale for a certain radiation mechanism is comparable with the dynamical timescale of the relativistic motion of the charges. The observed radiation is expected to occur around a distance characterized by a point on that equal-timescale line at which the critical energy of radiated photons for the corresponding parameters is equal to the observed bending energy. At any other distances, the cooling population of radiating charges, if it exists, will have a cooling spectrum with a bending energy either higher or lower than the observed one. In view of the common trait in the spectral behavior of most EGRET pulsars, it is very likely that if PSR B0656+14 has a spectrum with a photon spectral index around -1.5 at some energies below 100 MeV, it must start getting flatter toward low energy from above 20 keV as is required by the *RXTE* PCA upper limits. A bending energy higher than 20 keV for PSR B0656+14 suggests an emission location at a distance larger than a couple of 10^8 cm from the stellar center and the synchrotron radiation being the dominant emission mechanism for radiating charges with a typical pitch angle of about 0.1–0.001. Curvature radiation does not yield a reasonable emission location within the light cylinder. More observations with the *RXTE* and the future *International Gamma-Ray Astrophysical Laboratory* are very much desired for providing better statistics and helping to advance our understanding of high-energy emissions from neutron stars.

Up-to-date, existing observations show that except for the Crab, the bending energies for other gamma-ray pulsars are all higher than a few tens of keV, although many of them are not yet well determined. On the other hand, some observations also reveal possible nonthermal X-ray emissions around keV from some gamma-ray pulsars. However, they may have an origin different from that of the whole continuum from several tens of keV up to a few GeV. For example, the reported nonthermal emissions around 1 keV for the Geminga and PSR B1951+32 both have a photon spectral index of about -1.5 (Halpern & Wang 1997; Safi-Harb, Ögelman, & Finley 1995), which, together with their flux magnitudes, makes them a separate component from that of higher energies; see Figure 6 in Strickman et al. (1996) and Figure 2 in Chang & Ho (1997).

The current observation, because no pulsation was detected, cannot confirm the power-law component proposed in Greiveldinger et al. (1996) for PSR B0656+14. However, the estimated upper limits ensure that if that component is real, it must be mainly unpulsed. An unpulsed power-law spectrum is not easily attributed to magnetospheric emissions. Although in the analysis of Wang et al. (1998) the power-law component was not confirmed, its existence and being unpulsed could be a good example supporting the idea of the "electron-positron blanket" proposed by Wang et al. (1998). Future *AXAF* and *XMM* observations will be able to solve this issue.

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